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Reconfigurable Structure using Multifunctional Mechanized Materials for Threats Precognition and Neutralization

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Reconfigurable Structure using Multifunctional Mechanized Materials for Threats Precognition and Neutralization

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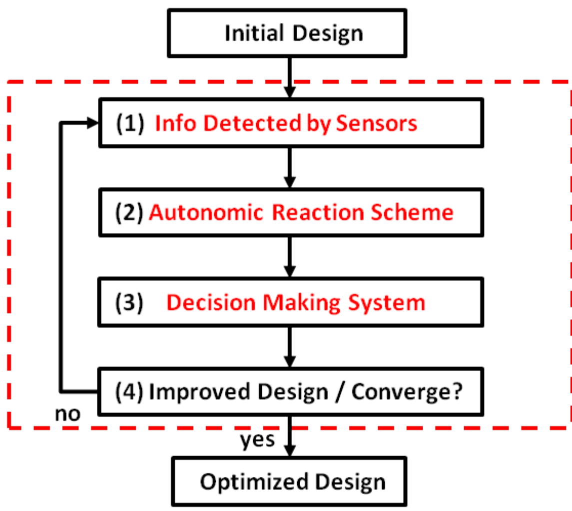
1. Objectives

The centerpiece of a reconfigurable structure is an autonomic nervous system (nervous system) that can coordinate the embedded sensor network (eyes) and adaptive mechanized materials (muscles) on the fight-or-flight response. Information detected from the sensor network is usually localized however the reactions from the mechanized materials must be globalized in order to neutralize the threats more effectively and efficiently. It is obvious that any pre-defined algorithm on the reaction scheme will fail to counter the unexpected threats. Therefore, a fully autonomic and reconfigurable structure must be self-sensing and self-actuating without any pre-defined scheme; the global structural morphosis resulting from any local information must be rooted in sophisticated and rigorous theories without any guessing work. To develop the fully adaptive multifunctional materials for reconfigurable structures, three important components must be integrated (1) embedded sensor network (eyes), (2) autonomic response system (nervous system) and (3) adaptive mechanized materials (muscles). Although many natural materials are remarkably adaptive reconfigurable structural materials, the complexity of their adaptive scheme and microstructures are far from the fabrication techniques one can afford today.

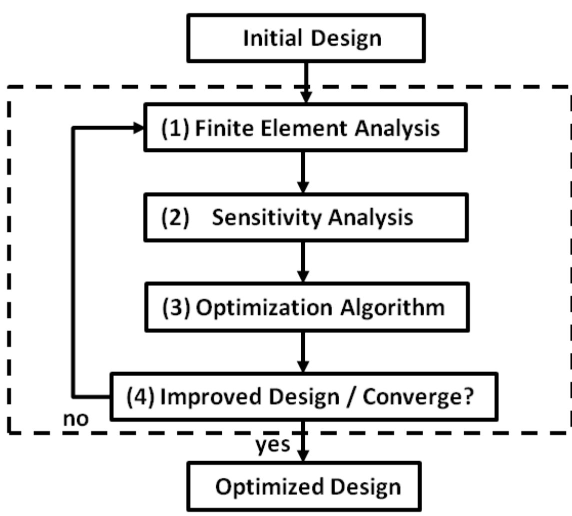
The proposed 3-year research project is a proof of concept project to take on this challenging problem. We plan to initiate the development and demonstration a novel concept of fully adaptive reconfigurable structures using multifunctional mechanized materials for threats precognition and neutralization. The main design concept of the proposed reconfigurable structures is when the incoming electromagnetic waves are detected by the skin sensors, and based on the location and intensity of the detected threats the underlying structure can reconfigure their shapes to neutralize the succeeding blast waves. Specifically, our goals are to develop a topology optimization based Autonomic Nervous System (ANS) and demonstrate the feasibility of the Adaptive Muscle System (AMS), for the reconfigurable structures using adaptive multifunctional mechanized materials. The main function of the ANS is to instruct individual adaptive mechanized material cell to reconfigure their shapes based on the location and intensity of the incoming electromagnetic waves detected to neutralize the succeeding blast waves. The instantaneously reaction of individual mechanized material cell will be realized by the AMS that is constructed by mechanized materials in order to neutralize the incoming threats. The building block of the mechanized materials is proposed to be a novel bi-stable cylindrical shell that can reconfigure itself very quickly in order to neutralize the incoming threats. Furthermore, performance robustness and device reliability will also be investigated.

2. Introduction

In the Autonomic Nervous System, the initial structure configuration should autonomously perform structural modification from the information received by local sensors based on an autonomic reaction scheme as shown in Figure 1(a). This autonomic reaction scheme is similar to a gradient search algorithm in the optimization process and the information received by local sensors can be simulated as the results from the finite element analysis as illustrated in Figure 1(b).



(a) Autonomic Nervous System



(b) Topology optimization

Figure 1: Flowcharts of (a) Autonomic Nervous System (ANS) and (b) Topology Optimization

3. Accomplishment

In the first year, the research program is focused on the development of a topology optimization based Autonomic Nervous System (ANS) for forced vibration responses and the feasibility study of the Adaptive Muscle System (AMS). Our first step is to complete the sensitivity derivations of a forced vibration system.

3.1 Autonomic Nervous System (ANS)

When a structure is subject to a forced vibration, the design goal is to reduce the magnitude of the vibration induced from the external harmonic loadings. Mathematically, we can define the dynamic compliance as the driving force times magnitude of the displacement and make minimizing the square of the dynamic compliance as the design goal as:

$$\min \quad c = \left(\boldsymbol{f}^T \boldsymbol{u}\right)^2$$

where $\boldsymbol{f}$ is the external driving force and $\boldsymbol{u}$ is the displacement of the forced vibration system. Assuming the external driving force has a fixed magnitude and is independent from the structure configurations. The sensitivity of the squared of the dynamic compliance can be simply expressed as the following:

$$\frac{\partial c}{\partial x_i} = \frac{2\partial(\boldsymbol{f}^T \boldsymbol{u})}{\partial x_i} = 2\boldsymbol{f}^T \frac{\partial \boldsymbol{u}}{\partial x_i}$$

where x_i represents the local stiffness variable, such as thickness. To evaluate the last term of the above equation, we consider the forced vibration system equation as:

$$(\boldsymbol{K} - \Omega^2 \boldsymbol{M})\, \boldsymbol{u} = \boldsymbol{f}.$$

and Ω is the frequency of external harmonic excitation, $\boldsymbol{K}$ and $\boldsymbol{M}$ are the stiffness and mass matrices. Taking the first derivative of the forced vibration system equation, can be written as:

$$\frac{\partial[(\boldsymbol{K} - \Omega^2 \boldsymbol{M}) \cdot \boldsymbol{u}]}{\partial x_i} = \frac{\partial(\boldsymbol{K} - \Omega^2 \boldsymbol{M})}{\partial x_i} \cdot \boldsymbol{u} + (\boldsymbol{K} - \Omega^2 \boldsymbol{M}) \frac{\partial \boldsymbol{u}}{\partial x_i} = 0$$

Pre-multiplying $\boldsymbol{u}^T$ to the above expression, we obtain:

$$\boldsymbol{u}^T \frac{\partial(\boldsymbol{K} - \Omega^2 \boldsymbol{M})}{\partial x_i} \cdot \boldsymbol{u} + \boldsymbol{u}^T (\boldsymbol{K} - \Omega^2 \boldsymbol{M}) \frac{\partial \boldsymbol{u}}{\partial x_i} = 0$$

We can replace the last term of the equation by the forced vibration system equation and move the first term of the equation to the right hand side as:

$$\boldsymbol{f}^T \frac{\partial \boldsymbol{u}}{\partial x_i} = -\boldsymbol{u}^T \frac{\partial (\boldsymbol{K} - \Omega^2 \boldsymbol{M})}{\partial x_i} \cdot \boldsymbol{u}$$

If the total mass of the system is constant, the sensitivity of the squared of the dynamic compliance can be derived as:

$$\frac{\partial c}{\partial x_i} = -2\boldsymbol{u}^T \frac{\partial \boldsymbol{K}}{\partial x_i} \cdot \boldsymbol{u}$$

Since the global stiffness is in an assembly of all local stiffness and the local stiffness is only related to the local stiffness variable. We can further reduce the sensitivity analysis as:

$$\frac{\partial c}{\partial x_i} = -2\boldsymbol{u}^T \frac{\partial \boldsymbol{k_i}}{\partial x_i} \cdot \boldsymbol{u}$$

where $\boldsymbol{k_i}$ represents the local stiffness matrix. Furthermore, if we assume the local stiffness can be expressed as the following form:

$$\boldsymbol{k}_i = f(x_i)\boldsymbol{k}_0$$

where $f(x_i)$ denotes the function of the local stiffness variables and $\boldsymbol{k}_0$ is the base local stiffness matrix. Then, the sensitivity analysis becomes:

$$\frac{\partial c}{\partial x_i} = -2\frac{\partial f(x_i)}{\partial x_i}\boldsymbol{u}^T\boldsymbol{k}_0 \cdot \boldsymbol{u} = -2\frac{\partial f(x_i)}{\partial x_i}\frac{1}{f(x_i)}\boldsymbol{u}^T f(x_i)\boldsymbol{k}_0 \cdot \boldsymbol{u} = -2\frac{\partial f(x_i)}{\partial x_i}\frac{1}{f(x_i)}\boldsymbol{u}^T\boldsymbol{k}_i \cdot \boldsymbol{u}$$

and $\boldsymbol{u}^T\boldsymbol{k}_i \cdot \boldsymbol{u}$ is two times of the local strain energy, e_i. Therefore, the sensitivity of the squared of the dynamic compliance arrived as:

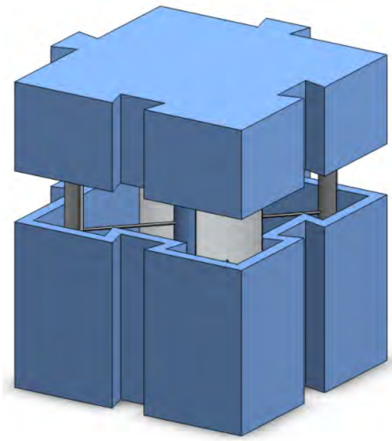
$$\frac{\partial c}{\partial x_i} = -4\frac{\partial f(x_i)}{\partial x_i}\frac{1}{f(x_i)}e_i$$

From the above derivations, we can conclude that the local autonomic reaction scheme can be evaluated completely based on the local measurement, such as local strain energy. Under this conclusion, the information detected by the individual sensor in the embedded sensor network of the multifunctional materials can work independently with its underlying mechanized materials to modify its local stiffness and improve the overall structural performance.

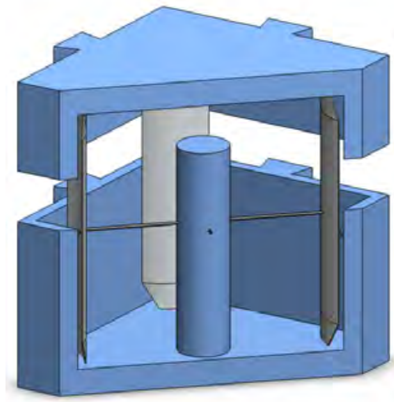
3.2 Adaptive Muscle System (AMS)

We have studied the feasibility of the design of AMS based on bi-stable structures enclosed in “cell capsules” with interlocking mechanisms, as shown in Figure 2(a). The cell capsules can contract or extend by morphing their supporting muscles. These muscles exhibit bi-stability with vertical and bent stable configurations, as illustrated in Figure 2(b) and (c), corresponding to two different heights of the cell. The transformation of the muscles can be actuated through an electric signal detected in memory alloy wires connected to the centers of muscles. When a pulse current is applied, the wires contract

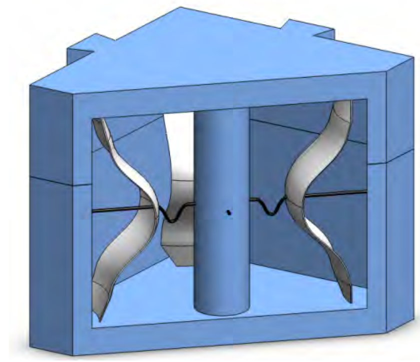
and pull the centers of muscles inwards, collapsing them into the bent configuration. A current is applied to the outer wires to pull the bent muscles outwards, placing them back into the vertical configuration.



(a) AMS unit cell



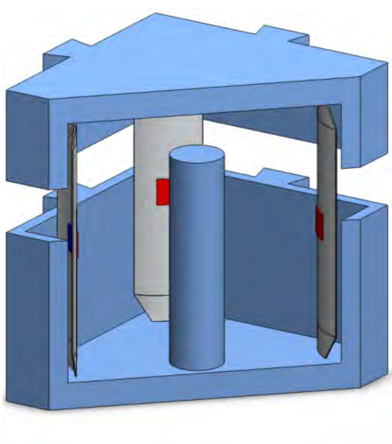
(b) Unit cell with bi-stable structures



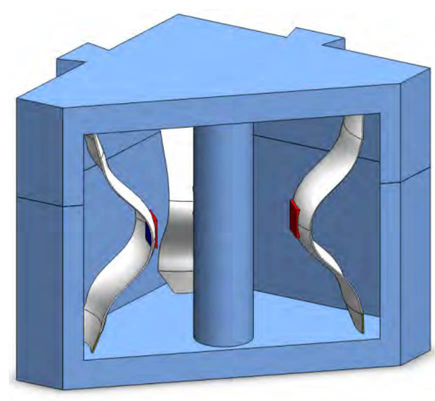
(c) Unit cell in a transformed configuration

Figure 2: Bi-stable Adaptive Muscle System

The AMS unit cell can also be based on magnets and current-induced magnetic fields as shown in Figure 3. This design eliminates the need for wires. It may be more appropriate for mass production and the fabrication of small scale structures. However, the main challenge that remains is the development of a mechanism to induce appropriate magnetic fields.



(a) Initial configuration

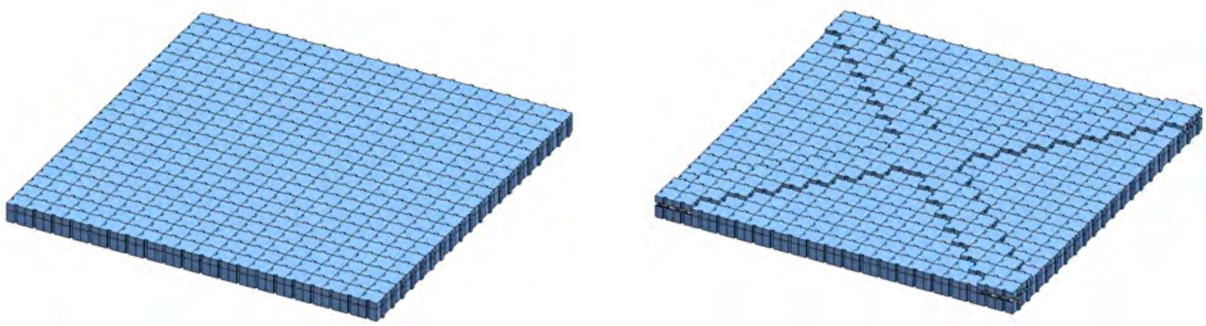


(b) Transformed configuration

Figure 3: Alternative design of multifunctional materials using magnets (red)

An important advantage of using bi-stable structures is the speed of reaction. The muscles react to the signal at an instance the wire starts contracting, and the transformation occurs in near real-time. Moreover, the design only requires an excitation to actuate the transformation. No energy input is required to maintain the structure in either state.

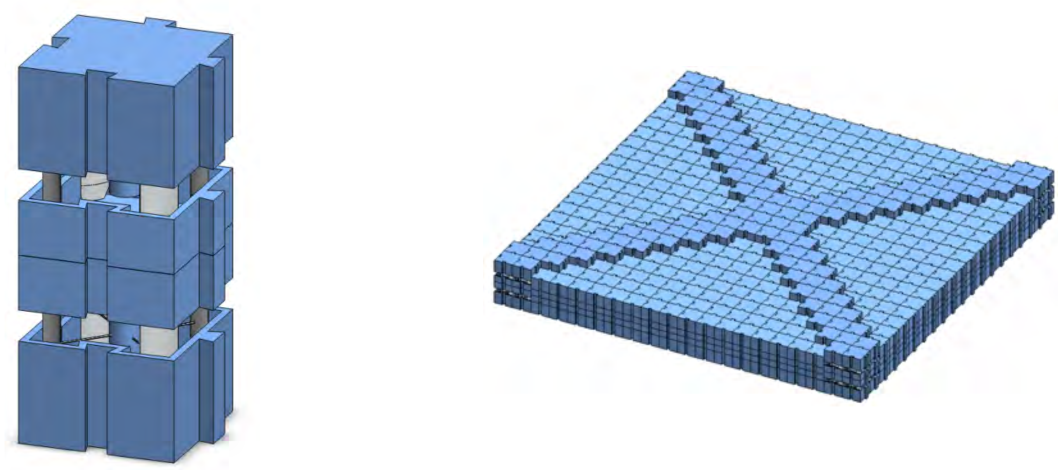
The exterior of the capsule is shaped such that the AMS cells can interlock with their neighbors and tile a flat surface, as shown in Figure 4(a). The interlocked cell walls will ensure the structure maintains its integrity against external loadings. Each cell's configuration will be adjusted autonomously to create a structure that meets the operational goal as shown in Figure 4(b).



(a) Initial structure (b) Morphed structure

Figure 4: Reconfigurable structures composed of multifunctional cells

Furthermore, multiple cells can be extended as stacking together to allow for multiple morphing states at each location as shown in Figure 5(a) and (b).



(a) Column of two unit cells (b) Reconfigurable structure

Figure 5: Reconfigurable structures composed of double-layered multifunctional cells

3.3 Uncertainty

The traditional topology optimization method often assumes all boundary conditions including external loadings are deterministic. However, the external loadings with uncertainty are very common in many practical engineering applications. Failure to include these uncertainties in the analysis model may results in a flawed "optimized" design which could lead to potential hazard in practice. Therefore, it is critically important to include uncertainty in the optimization models.

Considerable research development in this area has occurred in the last few decades such as the Reliability Based Topology Optimization (RBTO), proposed by Kharmand and Olhoff. Jung and Cho solved the three-dimensional geometrical nonlinearity problem by utilizing the RBTO framework. Ayyub developed the fuzzy sets concepts for structural design. The RBTO approach is based on a probabilistic model which requires a wide range of statistical data. A non-probabilistic model based approach called the Convex Model was introduced in 1990 by Ben-Haim and Elishakoff. Unlike the probabilistic models, the non-probabilistic model based approach does not require statistical data. Elishakoff and Ohsaki introduced the worst case design optimization concept, and Zhao et al. developed the Eigenvalue Superposition of Convex Models (ESCM). However, these models are limited in that they can only give an approximated solution due to the convex approximation process of a non-convex model.

In this project, a new approach has been developed in an attempt to address this critical limitation. First, the unknown-but-bounded uncertainty model is presented to formulate a mathematical model of an uncertain load. Second, a two level optimization problem is formulated. The upper level optimization problem is a deterministic topology optimization under a critical loading of the worst structure response, and the lower level optimization problem is to determine the critical loading corresponding to the worst structure response. The lower level optimization problem is then reformulated based on the KKT optimality conditions as an inhomogeneous eigenvalue problem and is solved for the critical loading corresponding to the worst structure response. After the worst loading case is identified, the upper level problem can be solved through existing gradient based optimization algorithms.

The design objective of the topology optimization problem is to find the optimal material distribution (optimal topology) which minimizes the mean compliance of the structure (the stiffest design) under the uncertain load conditions. Because of the load uncertainty, the external load often used in the traditional topology optimization formulation should be converted from a deterministic load to a non-deterministic load. Considering the worst case scenario design, the maximum mean compliance under the given uncertain load is selected as the new objective function in order to produce the safest design solution. Therefore, the problem shown in Figure can be described as a single level

optimization problem which is to find the optimum material distribution that minimizes the maximum mean compliance under the load uncertainty. To simplify the derivations, the uncertainty of the external load is formulated with a spheroidal-bounded model, which is a special case of the ellipsoidal-bound convex model. However, it can be easily shown that both models can be transformed directly.

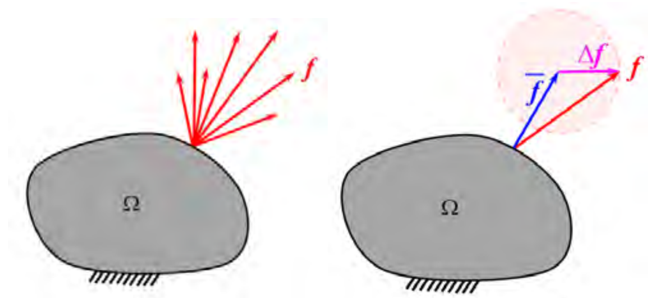


Figure 6: Topology Optimization Under Load Uncertainty

An example is shown in Figure , which decomposes the uncertain load *f* as a nominal load $\bar{f}$ and a perturbation load *Δf*, and the magnitude of the perturbation load *Δf* is bounded.

$$\begin{aligned} \min_{\boldsymbol{a}} \quad & C_{\max} = (\boldsymbol{u}^T \boldsymbol{K}\boldsymbol{u})_{\max} \\ \text{s.t.} \quad & V \le V_0 \\ & \boldsymbol{K}\boldsymbol{u} = \boldsymbol{A}\boldsymbol{f} \\ & \boldsymbol{f} = \bar{\boldsymbol{f}} + \Delta\boldsymbol{f} \\ & \Delta\boldsymbol{f}^T \Delta\boldsymbol{f} \le 1 \end{aligned}$$

Where a is the vector of the design variables. C_{max} is the mean compliance of the worst case response for that configuration. K and u are the global stiffness matrix and displacement vector of the structure. V and V_0 are the material volume and design domain volume, respectively. A is a localization matrix and its dimension is $N\times2$ for the 2 dimensional case and $N\times3$ for the three dimensional case.

The above single level optimization formulation can be converted into a two-level optimization formulation. The upper level optimization problem is formulated as a deterministic topology optimization under the critical load which leads to the worst structural response.

$$\begin{aligned} \min_{\boldsymbol{a}} \quad & C = \boldsymbol{u}^T \boldsymbol{K}\boldsymbol{u} \\ \text{s.t.} \quad & V \le V_0 \\ & \boldsymbol{K}\boldsymbol{u} = \underset{n\times 2}{\boldsymbol{A}}\ \underset{2\times 1}{\boldsymbol{f}} \end{aligned}$$

Since the upper level topology optimization problem is under a deterministic load which has the worst structural response, the main challenge then becomes identifying the critical load that has the worst structure response (the maximum strain energy). To find the critical load, the lower level optimization problem is formulated as:

$$\begin{aligned} \max_{\Delta \boldsymbol{f}} \quad & C = \boldsymbol{f}^T \boldsymbol{A}^T \boldsymbol{K}^{-1} \boldsymbol{A} \boldsymbol{f} \\ \text{s.t.} \quad & \boldsymbol{f} = \overline{\boldsymbol{f}} + \Delta \boldsymbol{f} \\ & \Delta \boldsymbol{f}^T \Delta \boldsymbol{f} \le 1 \end{aligned}$$

From the equality constraints $Ku=Af$ and $f = \bar{f} + \Delta f$, the lower level problem can be simplified as

$$\begin{aligned} \min_{\Delta \boldsymbol{f}} \quad & -(\overline{\boldsymbol{f}} + \Delta \boldsymbol{f})^T \boldsymbol{Q} (\overline{\boldsymbol{f}} + \Delta \boldsymbol{f}) \\ \text{s.t.} \quad & \Delta \boldsymbol{f}^T \Delta \boldsymbol{f} \le 1 \end{aligned}$$

where $Q=A^TK^{-1}A$ is a positive definite form inversion of the reduced global stiffness matrix. For the single load in the two dimensional case, the dimension of the Q matrix is a two by two matrix which is much smaller than N by N dimensions from the global stiffness matrix K. The lower level problem will find the external load that causes the worst structure response and the external load will be applied into the upper level problem. The upper level optimization problem will distribute materials to minimize the compliance of the structure for the worst case scenario. The lower level problem can be solved by the Karush-Kuhn-Tucker (KKT) necessary conditions. The KKT necessary conditions can be reduced as the following inhomogeneous eigenvalue problem:

$$\begin{aligned} & (\boldsymbol{Q} - \lambda \boldsymbol{I}) \Delta \boldsymbol{f} = -\boldsymbol{Q} \overline{\boldsymbol{f}} \\ & \Delta \boldsymbol{f}^T \Delta \boldsymbol{f} = 1 \end{aligned}$$

From all of the eigenvalues that were calculated, it is necessary to find out which eigenvalues are the maximum points of the original optimization problem. In order to find out the corresponding eigenvalue λ^*, the 2nd order sufficient conditions are applied to identify the optimal solution from the candidates.

$$\frac{d^2 L}{d\left(\Delta \boldsymbol{f}\right)^2} = -2\boldsymbol{Q} + 2\lambda \boldsymbol{I} \succeq \boldsymbol{0}$$

Once λ^* is selected, the perturbation load will be the corresponding eigenvector and then the worst structure response loading can be simply calculated.

4 Personnel

In addition to the Principal Investigator, Prof. Hae Chang Gea, two post-doctor associates supported under this research program are:

- Kazuko Fuchi, Currently with Air Force Research Laboratory (Dayton, Ohio)
- Euihark Lee, Rutgers University

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14. ABSTRACT

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Abstract

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